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Optical pavement treatments and their impact on speed and lateral position at transition zones: A driving simulator study

Qinaat Hussain [a,**], Wael K.M. Alhajyaseen [a,*], Nora Reinolsmann [b], Kris Brijs [b], Ali Pirdavani [b], Geert Wets [b], Tom Brijs [b]

[a] Qatar University – Qatar Transportation and Traffic Safety Center, College of Engineering, P.O.Box 2713, Doha, Qatar
[b] UHasselt, Transportation Research Institute (IMOB), Agoralaan, 3590, Diepenbeek, Belgium

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ABSTRACT

Transition zones are a road section where posted speed drops from higher to lower limits. Due to the sudden changes in posted speed limits and road environment, drivers usually do not adapt to the posted speed limits and underestimate their traveling speed. Previous studies have highlighted that crash rates are usually higher in these sections. This study aims at improving the safety at transition zones by introducing perceptual measures that are tested using a driving simulator. The proposed measures are speed limit pavement markings with a gradual increase of brightness and/or size that were placed at transition zones in simulation scenarios replicating the real-world environment of the Doha Expressway in Qatar. These innovative measures aim to produce the impression of increased speed that could stimulate drivers to better adapt speed limits. The driving behavior of 81 drivers possessing a valid Qatari driving license was recorded with a driving simulator interfaced with STISIM Drive® 3. Results showed that pavement markings combining size and brightness manipulations were the most effective treatment, keeping drivers' traveling speed significantly below the traveling speed recorded in the untreated control condition. In this regard, the maximum mean speed reductions of 5.3 km/h and 4.6 km/h were observed for this treatment at the first transition (120 to 100 km/h) and second transition (100 to 80 km/h) zones, respectively. Regarding the variations in drivers' lateral position, the results showed that the proposed pavement markings did not negatively influence drivers' lateral control on the road as the maximum observed standard deviation of lateral position was around 0.065 m. This study shows that the proposed pavement markings are recommended for improving the speed adaptation of drivers in the transition zones.

1. Introduction

1.1. Safety at transition zones

The term transition zone refers to road segments, where a higher speed limit changes into a lower speed limit (Forbes, 2011). Research indicates that transition zones are challenging in terms of traffic safety (Akbari & Haghighi, 2019; Ariën et al., 2013; Galante et al., 2010). Tziotis (1992) found that Victoria's crash rates are markedly higher at transition zones than on rural roads, i.e., 45 vs. 27 fatalities per 100 million vehicle-kilometers, respectively. According to Akbari & Haghighi (2019), more than 23% of all fatal crashes in Iran occur in rural-urban transition zones. In Italy, road traffic crashes and fatalities from road traffic crashes recorded at transition zones accumulate to 14.5% and 33.2% of total urban crashes and fatalities, respectively (Lamberti et al., 2009).

It is a well-known fact that driving itself is a complicated task. How the road environment has been designed sometimes contributes to that complexity, for instance, when speed limits suddenly drop, as is the case in transition zones (Ariën et al., 2014; Ariën et al., 2013; Galante et al., 2010; Tziotis, 1992). One possible explanation is that road users simply fail to attend to the information aimed at guiding, controlling, or regulating traffic. For instance, Costa et al. (2014) showed that mean attendance frequency for vertical traffic signs in general and more specifically for speed limit signs was only 25.06% and 32.06%, respectively. According to Ariën et al. (2013), safety at transition zones can be

* Corresponding author.
** Corresponding author.
E-mail addresses: qinaat.hussain@qu.edu.qa, qinaat.hussain@uhasselt.be (Q. Hussain), wyaseen@qu.edu.qa (W.K.M. Alhajyaseen), nora.reinolsmann@uhasselt.be (N. Reinolsmann), kris.brijs@uhasselt.be (K. Brijs), ali.pirdavani@uhasselt.be (A. Pirdavani), geert.wets@uhasselt.be (G. Wets), tom.brijs@uhasselt.be (T. Brijs).

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compromised when driving task complexity imposes too much workload on transitioning drivers due to the road environment's changes and speed limit. This could increase the possibility of driving errors, such as the poor adaptation of speed and lateral positioning while entering lower speed zones (RISER, 2006). Therefore, it is crucial to provide appropriate countermeasures to assist drivers in adapting speed in the lower speed zones.

In general, drivers do not necessarily adapt to the posted speed limits (Elvik et al., 2004) and may travel faster than the posted speed limits (Stephens et al., 2017). In transition road sections, the speed adaptation becomes more complicated since posted speed changes from higher into lower limits (Casey & Lund, 1987; Denton, 1976), which commonly lead to over speeding in the lower speed limit road section. This can be attributed to the fact that following a long period of driving at a higher speed limit, drivers may overestimate their speed reductions as they pass through from a higher speed regime to a lower speed regime (Cao et al., 2015; Denton, 1966; Forbes, 2011; Hallmark et al., 2007; Schmidt & Tiffin, 1969). As speed influences both the probability of a crash and its severity (Alhajyaseen, 2015, Aarts & van Schagen, 2006; Heydari et al., 2014), there is a potentially increased accident risk at transition zones where speed limit exceedance could be more prevalent due to speed adaptation. Schmidt & Tiffin (1969) recommended that speed adaptation should be considered while designing certain parts of the road network such as curves at the end of long tangents and road stretches where speed transition occurs.

Inappropriate lateral positioning is one of the main factors that lead to run-off the road and head-on collisions (RISER, 2006). According to De Waard et al. (2004), adding painted materials to the road surface could affect drivers' lateral position on the road. In their study, a centerline added to the road resulted in reduced lateral position variations. However, adding additional elements caused a small increase in the lateral position. Besides, previous studies considered variations in lateral position as a gauge to evaluate if the countermeasures have any negative influence on driving behavior (Ariën et al., 2013; Ariën et al., 2014; Hussain et al., 2018; Merat & Jamson, 2013; Simmons et al., 2017). Therefore, this study also considers variation in lateral position as one of the study parameters.

1.2. Speed-related perceptual pavement treatments

Driving simulators have become an important tool to incorporate human factors in road safety research (Fisher et al., 2011; Llopis-Castelló et al., 2016). Driving simulators can be used to evaluate the performance of different solutions before the real-world implementation, such as optical pavement markings (Ariën et al., 2014; Ariën et al., 2017; Ariën et al., 2013; Calvi, 2018; Calvi et al., 2019; Charlton et al., 2018; Galante et al., 2010; Godley et al., 2004), variable message signs (Guattari et al., 2012; Meuleners et al., 2020; Reinolsmann et al., 2019), intelligent transportation system ITS-based technologies (Hussain et al., 2020a; Larue et al., 2015) and in-vehicle or connected environment (Lin et al., 2008; Yang et al., 2020), etc. In addition, simulators offer a safe environment to investigate complex conditions that could not be safely studied in real-world, such as cell phone use while driving (Rumschlag et al., 2015; Wijayaratna et al., 2019), adverse weather conditions (Chen et al., 2019; Shangguan et al., 2020), drowsiness and fatigue (Merat & Jamson, 2013; Wang et al., 2017; Hallvig et al., 2013), night-time scenarios (Bella et al., 2014; Calvi & Bella, 2014; Nygårdhs et al., 2014), and alcohol use (Vollrath & Fischer, 2017), etc.

Traffic calming measures refer to various design features and strategies intended to alter driver behavior to reduce vehicle use's adverse effects and improve road safety (Ewing, 1999). They are often used to manage traffic speeds and capacities on a particular road (Kjemtrup & Herrstedt, 1992). Various types of traffic calming measures have been used to stimulate motorists to lower their travel speeds (Hallmark et al., 2007):

- Physical measures, such as road narrowing (Goralzik & Vollrath, 2017; Mecheri et al., 2017; Montella et al., 2011), build-outs (Ariën et al., 2014; Galante et al., 2010; Vignali et al., 2019), and chicane (Distefano & Leonardi, 2017)
- Surface treatments, such as rumble strips (Ariën et al., 2017), pavement markings (Ariën et al., 2017; Godley et al., 2004), and perceptual countermeasures (Auberlet et al., 2012; Calvi, 2018; Calvi et al., 2019; Hussain et al., 2018; Montella et al., 2015)
- Traffic enforcement, such as speed cameras (Li & Graham, 2016; Polders et al., 2015)

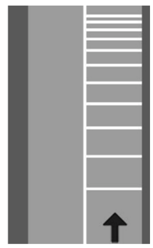
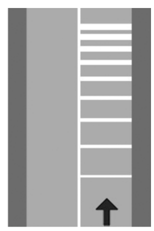
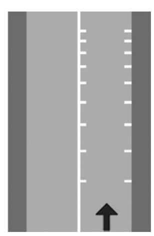
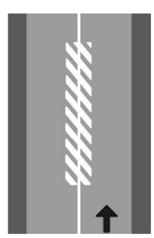
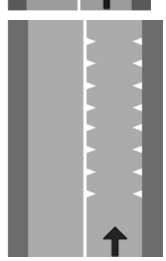
In transition zones on highways with higher posted speed limits (e.g., 120 to 100 km/h), physical treatments could create additional hazards while traffic enforcement could be an expensive option. According to the Danish Road Directorate (2013), in the case of roads with higher posted speed limits, the most feasible option is to use informative speed-reducing measures such as surface treatments. Low-cost pavement markings can be used on the road surface to influence drivers' speed choice by creating an impression of increased speed (Denton, 1971). A summary overview of different strategies used to alter drivers' speed and lane/road width-related perceptions is provided in Table 1. Most of these strategies were tested in driving simulator (DS) experiments with data collected from 15 to 48 participants. Transverse optical bars with progressively reduced spacing, optical bars with progressively increased width and reduced spacing, and peripheral transverse optical bars with progressively reduced spacing were used to induce a perception of increased traveling speed.

On the other hand, wide painted center/edge markings, dragon's teeth markings, and herringbone markings were used to produce a perceptual road narrowing effect. According to Godley et al. (2004), the perception of road narrowing stimulates drivers to reduce their travel speed. Furthermore, two studies used solid filled circles while one study used speed limit markings with increased size in the traveling direction to create impressions of increased speed and road narrowing effect. In a preliminary study, Samson et al. (2020) used the idea of size manipulation using speed limit pavement markings at a 120 to 100 km/h transition zone. However, the current study introduced novel ideas of manipulating luminance (i.e., brightness) and combined size and luminance concepts in optical pavement treatments.

1.3. Manipulation of size and luminance in optical pavement treatments

Studies that have investigated the effects of optical ground surface treatments (Feria et al., 2003; Wul et al., 2004; Ding et al., 2019) have based their research on Gibson's fundamental Ground theory (Gibson, 1950). It states that human beings cannot establish a reliable reference frame for obtaining correct distance and speed estimations when the common ground surface is disrupted (i.e., discontinued). Feria et al. (2003) referred in their study to the "discontinuity effect", which contributes to underestimating distance due to the discontinuous ground surface. In the research by Ding et al. (2019) ' a specific type of discontinuous linear edge marking was implemented on the highway to investigate drivers' car-following behavior. The results showed that drivers' headway increased while reducing speed. Wu et al. (2007) tested the convergent linear perspective marking. Compared with a parallel marking, it could result in distance overestimation. They found that if two lines are purposefully paved with the far end pointing inwards on the ground surface, the viewer would perceive the paired lines as distant. In contrast, Ding et al. (2019) applied the concept of divergent lines to influence driving behavior in work zones, and particularly to achieve distance underestimation to the vehicles ahead. The on-road study results revealed that the visual intervention on drivers' distance perception through an outward-pointing angle could be used as a countermeasure for safety issues related to fast approaching speeds. This divergent effect in the distance can also be attained by successively increasing the size of paved circles in the center of the driving lane since

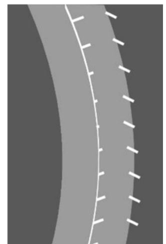
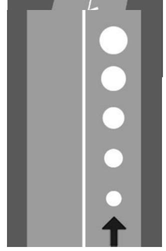
Table 1
Summary of different optical strategies in the literature

Effect	Optical strategy	Design	Studies	Findings
1. Impression of increased speed	1a) Transverse optical bars (TOB): The spacing between bars reduced progressively in the traveling direction		Arnold & Lantz (2007) (before and after study on transition zones)	No conclusions can be drawn as the speed decreased at one transition zone, but it increased at another
			Ding et al. (2013) (DS study based on 15 subjects and used double bars)	Up to 10 km/h speed reduction along interchange with a vertical crest curve
			Godley et al. (2000) (DS study based on 23 subjects and evaluated two types of TOB, i.e., with reduced spacing and with constant spacing)	Up to 9.26 km/h speed reduction before the intersections and no significant difference between both types of TOB
			Maroney & Dewar (1987) (before and after study across an exit ramp of freeway)	2.02 km/h speed reduction
			Matírnez et al. (2013) (field study based on 33,548 measurements)	The study used TOB in conjunction with other different measures
	1b) Optical bars (OB) with varying width: The spacing between bars reduced AND the width of bars increased progressively in the traveling direction		Galante et al. (2010) (driving simulator study based on 30 subjects)	The study used OB in conjunction with other measures
			Hussain et al. (2018) (driving simulator study based on 44 subjects)	3.7 km/h speed reduction, 100 m before the transition zone AND standard deviation of lateral position (SDLP) values ranged from around 0.08 to 0.108 m
			Montella et al. (2011) (DS study based on 30 subjects)	The study used OB in conjunction with other measures AND SDLP values ranged from 0.24 to 0.35 m
	1c) Peripheral transverse optical bars (PTOB): Spacing between each pair of bars reduced progressively in traveling direction		Fildes et al. (2005) (field study on six intersections in Victoria, Australia|)	0.1 to 1.0 km/h reduction of mean speed before the intersections AND no significant difference in lateral position compared to the control condition
			Galante et al. (2010) (DS study based on 30 subjects)	The study used PTOB in conjunction with other measures
			Gates et al. (2008) (before and after study on freeway curves)	1.6 to 6.4 km/h speed reduction
			Godley et al. (2000) (DS study based on 23 subjects)	Up to 6.61 km/h speed reduction before the intersections
2. Perceptual road narrowing effect	2a) Road center/edge marking: Wide painted (hatched) centerline or edge markings		Godley et al. (2004) (DS study based on 28 participants and used hatched centerline markings)	Up to 3.1 km/h speed reduction on curves while 1.5 km/h on straight roads AND SDLP values of around 0.135 to 0.185 m
			Lum (1984) (used painted edge lines to reduce the lane width from 4.25 to 2.7 m)	No significant differences in speed were found
	2b) Dragon's teeth markings (DTM): Triangular road markings placed on both sides of the lane with equal spacing		Galante et al. (2010) (DS study based on 30 subjects)	The study used DTM in conjunction with other different measures
			Montella et al. (2011) (DS study based on 30 subjects)	The study used DTM in conjunction with rumble strips And SDLP values ranged from 0.38 to 0.43 m
			Rossi et al. (2014) (DS study based on 28 subjects and curve sections)	No significant differences in speed and lateral position were found
	2c) Herringbone markings (HM): Based on Herringbone pattern and placed on both sides of the lane with equal distance		Ariën et al. (2017) (DS study based on 32 subjects and curve sections)	No significant differences at the entrance and middle of the curve, while 2.5 to 3.5 km/h speed reduction at the 3rd quarter of the curve AND mean lateral position values were not significantly different
			Charlton (2007) (DS study based on 48 subjects and curve sections)	2.7 to 5.3 km/h of speed reduction; AND lateral displacement ranged from around1.3

(continued on next page)

advance warning signs and chevron sight board

Table 1 (*continued*)

Effect	Optical strategy	Design	Studies	Findings
			Godley et al. (1999) (DS study based on 24 to 36 subjects and rural straight road section	Mean speed reduction of 2.03 km/h compared to the control condition
			Awan et al. (2019) (DS study based on 43 subjects and curve sections)	Around 2 to 5 km/h speed reduction at the entrance of the curves; however, speed increased after the middle of the curves AND lateral position values ranged from around 1.7 m to 2.2 m
3. Combined effects (impression of speed increase and road narrowing)	3a) Optical circles: Solid filled circles with increased size progressively in traveling direction		Awan et al. (2019) (DS study based on 43 subjects and curve sections)	Around 1 to 5 km/h speed reduction that lasted until the middle of the curves AND lateral position values ranged from around 1.7 m to 2.2 m
			Hussain et al. (2018) (DS study based on 44 participants and rural-urban transition zones)	Up to 5.8 km/h speed reduction before the transition zone entrance AND SDLP values ranged from around 0.075 to 0.107 m

the visual angle is influenced by increasing circle sizes that lead to an underestimation of perceived distance. So far, two studies have demonstrated a decrease in speed when white-filled circles with increasing sizes were implemented in transition zones (Hussain et al., 2018) and curves (Awan et al., 2019). Both studies found that drivers' speed was significantly reduced while driving for the treatment condition. According to Hussain et al. (2018), the observed speed reductions can be understood as response to a road-narrowing effect and impression of increased speed, induced by the progressively increasing size of the circles, which reduces free space between the circles' circumference and the roadside edge and reduced longitudinal distances between two consecutive circles, respectively. Moreover, Kirsti (2007) and Knight et al. (2006) referred to this effect as a forced perspective illusion since the paved object size can create a false perception of distance, i.e., bigger size objects appearing more nearby than smaller ones. This phenomenon was studied by other researchers where similar results were reported (DeLucia, 1991; Epstein & Landauer, 1969; Gogel, 1964; Higashiyama, 1977; Higashiyama & Adachi, 2006; Landauer & Epstein, 1969; Ross & Plug, 1998). This, in turn, could stimulate drivers to reduce their driving speeds while approaching the transition zone with painted circles of increasing sizes.

Besides the geometrical characteristics of these markings (e.g., shape, position, direction, size), the brightness or contrast of colors can also be manipulated to influence the perception of depth and relative distances (Idesawa, 1997). Luminance refers to a color's perceived brightness and substantially influences visual perception (Lin, 2013). Sundet (1978) argued that the perceived relative distance could be influenced by the relative brightness of colored objects, i.e., brighter colors could be perceived nearer than darker ones. In an experimental study on brightness differences, Taylor and Sumner (1945) observed that light colors are perceived as closer than dark colors. Also, according to Camgöz et al. (2003), colors with maximum saturation and brightness attract the most attention. This was further verified by Qian et al. (2018), who reported that the effects of depth perception on Visual Working Memory (VWM) are responsible for maintaining and processing visual information from the driving environment. In their laboratory study, the authors employed a change detection paradigm that is based on the fact that perceptually closer-in-depth items, by which light is directly reflected to the eyes, are more conspicuous than farther items of different size and depth cues (i.e., depth perception through changes in distance and brightness). Particularly, the effects of saturation and brightness on VWM were investigated in several experiments by varying the tested stimuli' appearance and brightness. According to the authors, brightness and saturation stimuli could improve the change detection accuracy. Moreover, memory performance was improved for perceptually closer stimuli over farther ones. The mentioned findings indicate that both depth perception (e.g., saturation and brightness) and visual salience improve the ability to remember nearby stimuli through the underlying mechanism of priority setting for attentional selection.

The literature review suggested that a divergent linear perspective through the application of paved markings that gradually increase in size and brightness towards the traveling direction can impact drivers' distance perception. This is based on the assumption that every next marking could be perceived nearer than its original position, which results in an impression of increased speed and, hence, triggers drivers to lower their actual travel speed. As mentioned in the literature, Hussain et al. (2018) used solid-filled circles with increased size in the traveling direction to trigger drivers' travel speed at a transition zone of 70 to 50 km/h. However, in this study, the depth perception is created by pavement markings (i.e., speed limit encircled) that change in size and/or brightness and placed at two transition zones (i.e., 120 to 100 km/h and 100 to 80 km/h) to manipulate the distance perception. Furthermore, it is important to mention that the study is based on the driving population in the State of Qatar, which is characterized by very high diversity in terms of various ethnicities and cultural backgrounds (Soliman et al., 2018; Timmermans et al., 2019; Timmermans et al., 2020).

2. STUDY OBJECTIVES

The main objective of this driving simulator study is to evaluate the effectiveness of optical pavement treatments on driver behavior in terms of their traveling speed and lateral position at double transition zones (i.e., Transition 1: from 120 km/h to 100 km/h, and Transition 2: from 100 km/h to 80 km/h). Three specific optical pavement treatments will be implemented, i.e., speed limit sign pavement marking gradually increasing in brightness (i.e., "Brightness" condition); speed limit sign pavement marking gradually increasing in size (i.e., "Size" condition), and speed limit sign pavement marking with a combined gradual increase of brightness and size (i.e., "Combined" condition). These three conditions will be compared with a control condition (i.e., a static roadside speed limit sign is present, but no additional speed limit pavement marking is offered). The first objective is to test whether (and to what extent) the three proposed optical pavement treatments influence drivers' traveling speed at the transition zones. The second objective is to investigate if the three proposed optical pavement treatments influence the standard deviation of lateral position (SDLP) at the transition zones.

3. METHODS

3.1. Simulation apparatus

The driving simulation experiment was performed using the fixed-base driving simulator at Qatar Transportation and Traffic Safety Center (QTTSC), Qatar University. The simulator validity has been examined in terms of external validity (i.e., real speed and perception speed), and subjective validity (Hussain et al., 2019a). This simulator is also validated for the geometric field of view offered by the simulation screens in terms of speed perception (Hussain et al., 2020b). The validation studies confirmed satisfactory results on actual speed and speed perception, proving the apparatus's validity to be employed in the study. The driving simulator's cabin is a Range Rover Evoque in which an automatic transmission gearbox, speedometer, force-feedback steering wheel, pedals, and indicators have been equipped to create a close-to-production cockpit (see Fig. 1). Three front-view large screens providing 135 degrees field of view, resolution of 5760 × 1080 pixels, and update rate of 60 Hz have been implemented. These components are interfaced with STISIM Drive® 3 and the CalPot32 program, which offers high-speed graphics and sound processing (Eriksson et al., 2018). A wide range of data can be obtained from the simulator, such as speed, lateral/longitudinal position, acceleration, crashes, red-light violations, speed violations, inputs of pedals, and reaction time, etc.

3.2. Participants

In total, 81 drivers holding valid Qatari driving license type B (eligible for all types of passenger cars) took part in this study voluntarily without any compensation for their partcipication.. The recruitment process was started by emailing Qatar University-affiliated people as the first goal society and continued by posting information on social media platforms with the web portal of registration (www.qatardrivingsimulator.com) to include drivers from outside of the campus. Following the standard simulation sickness questionnaire presented by Kennedy et al., 1993, all participants were advised to avoid eating or drinking at least two hours before the test time (except water). However, the participation of the three volunteers was excluded from further analysis. Two volunteers were unable to complete the test due to simulation sickness symptoms, and another volunteer was identified as an outlier. Thereby, the number of 78 drivers ranging from 19-69 years with an average of 24.79 and SD = 7.9 years from 19 different nationalities included in the test, in which 70.5% were men, and 29.5% were women. Participant individuals had 1-49 years driving background with a mean of 5.69 years and SD = 6.8 years. More than 80% of volunteers had driven more than 10,000 km a year, in which 46.7% was over 20, 000 km experience of driving.

3.3. Scenario design

Two test drives of approximately 16 kilometers each, were designed for this experiment. The simulation contexts of both test drives were replicating the current road layout and surrounding environment (e.g., road markings, median and roadside signs)of Doha Expressway as realistic as possible with video footage and Google earth images of the Doha Expressway, using STISIM Drive® interface. Roadway sections consisted of 3-lanes in both directions with a lane width of 3.65 m. Speed limit signs were placed precisely at the transition points. Furthermore, the scenarios were designed for daylight and favorable weather conditions with a clear view.

Each test drive contained two sets of double transition zones. The double transition zones were separated from each other using a one-kilometer long road segment. In the first transition zone, the speed limit dropped from 120 to 100 km/h (moving from rural area to sub-urban area), and in the second transition zone, the speed limit was

Fig. 1. Driving simulator: Qatar Transportation and Traffic Safety Centre (QTTSC), Qatar University.

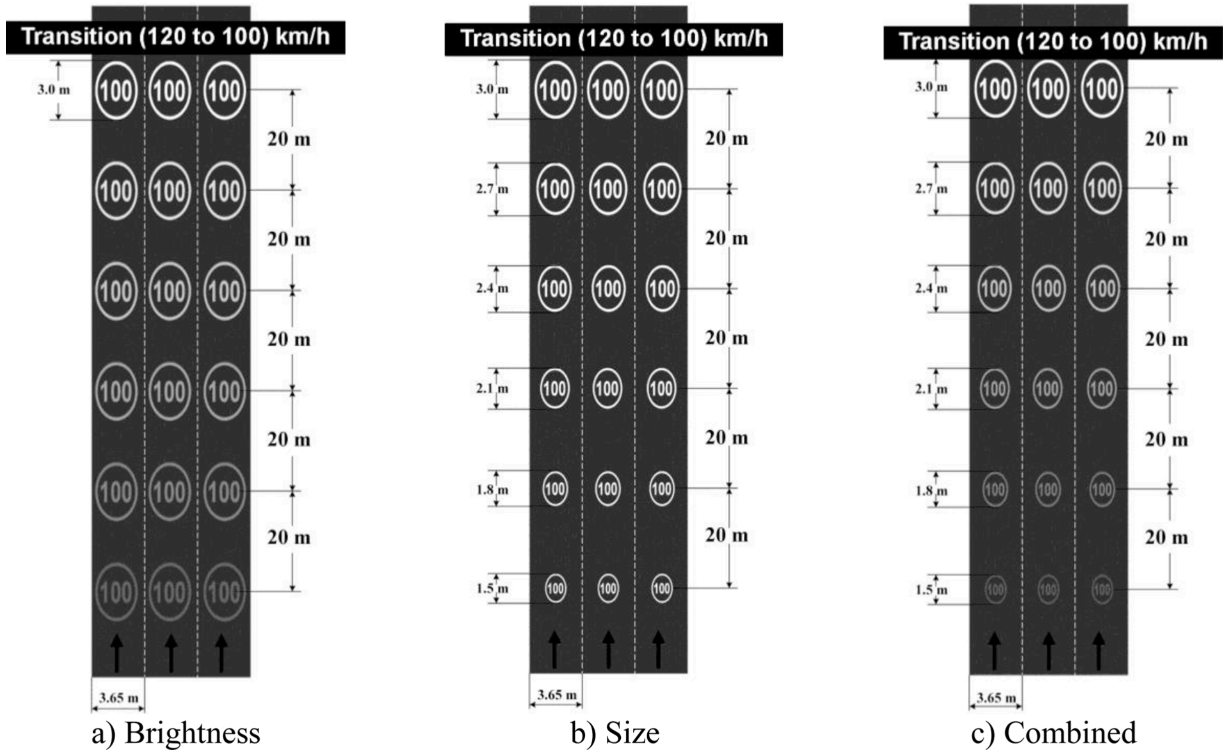


Fig. 2. Overview of pavement marking treatments as implemented at 120 to 100 km/h transition zones

further reduced from 100 to 80 km/h (moving from sub-urban area to urban area). The two sets of double transitions were designed as level and tangent road sections, and they were supplemented by a variety of filler pieces. The filler pieces included different types of situations (e.g., work zones and pre-programmed events, such as vehicles executing a specific maneuver, horizontal curves, and overhead bridges) to create some diversity and reduce the probability of learning effects to occur and bias the results.

Four sets of double transitions were designed (two in each test drive) on the Doha Expressway, each of them replicating one of the four tested conditions. The tested conditions were placed in randomized order between the test drives and between the first and second set in the test drives. The "Control" condition was a standard double transition zones with static roadside speed limit signs (100 km/h speed limit sign was placed at the first transition while 80 km/h speed limit sign at the second transition), but without additional speed limit pavement markings. As already indicated, the "Control" condition was compared with three specific test conditions of speed limit sign pavement markings, i.e., gradually increasing in brightness (i.e., "Brightness" condition) as shown in Fig. 2a; gradually increasing in size (i.e., "Size" condition) as shown in Fig. 2b, and combined gradual increase of brightness and size (i.e., "Combined" condition) as shown in Fig. 2c.

In the "Brightness" condition (see Fig. 2a), six sequential speed limit pavement markings with a diameter of 3.0 m were installed on a road segment covering 100 m with an intermediate distance of 20 m from center to center. "Brightness" of the markings increased progressively by 15% in the traveling direction, with the brightness of the first speed limit marking set at 25% of the standard grayscale (Johnson, 2006). The brightness treatment's intended purpose was to produce the optical effect where the brighter circles would be perceived as more nearby. This, in turn, was assumed to stimulate drivers to lower their speed.

The "Size" condition (see Fig. 2b) was comparable to the "Brightness" condition in terms of spacing and alignment (i.e., a 100 m segment with six sequential speed limit pavement markings at an intermediate distance of 20 m from center to center), but was different in terms of size. More in detail, the diameter of the speed limit markings increased progressively with a constant ratio of 0.3 m, starting from 1.5 m for the first marking up to 3.0 m for the last marking. The markings were increased in size with a linear trend based on the size-distance invariance hypothesis, which indicates that the rental size/angle (θ) has an inverse (linear) relationship while the size of an object (S) has a direct relationship with the perceived distance (D) as described by Gogel (1963) and Kilpatrick & Ittelson (1953) in equation (1), where k is the constant.

$$D = \frac{S}{(\theta)\ (k)} \tag{1}$$

This size manipulation aimed to create the optical effect where the larger circles would be perceived as more nearby. This, in turn, was expected to stimulate drivers to lower their speed.

Finally, the "Combined" condition (see Fig. 2c) was based on the same spatial and alignment features as those adopted in the previous two conditions (i.e., a 100 m segment with six sequential speed limit pavement markings at an intermediate distance of 20 m from center to center). However, both the brightness and size of the speed limit markings were manipulated simultaneously as in the "Brightness" and "Size" conditions. The ultimate goal of this treatment was to create a combined optical effect (i.e., increased brightness and size together, suggesting shorter distance) so as to stimulate drivers to lower their speed.

3.4. Experimental procedure

Ethical approval for this study was obtained from the Institutional Review Board (QU-IRB). The completion of the total experimental procedure took about one hour per participant. Upon arrival, participants signed an informed consent form. Next, they answered a pre-test questionnaire probing for driving experience and a selection of sociodemographic aspects. After that, participants familiarized themselves with the simulation mockup through a try-out scenario of approximately 7 km long. This warm-up scenario replicated a segment of the Corniche road of Doha City, Qatar. Before being exposed to the test scenarios, participants were instructed to drive as they would typically do.

Furthermore, they were informed that they could quit the experiment for any reason and anytime. Next, the participants drove both test drives with a short break, implying that he or she was confronted with four double-transitions randomly, one for each condition. After completing the test scenarios, participants filled out a short post-test questionnaire and were asked for feedback and thoughts on the driving simulator and the treatments applied in the experiment.

3.5. Data analysis

To achieve high accuracy speed and lateral position data were collected in very small intervals, i.e., less than every tenth of a second (i.e., 0.0995 s). The available data was configured as per meter for each variable. The entire analysis section for each condition covered a total length of 300 m, i.e., 200 m before the transition point and 100 m after the transition point. Within this area of interest, drivers' travel speed data was extracted at seven consecutive points at an equal interval of 50 m. For each participant, this data extraction was done for all the four conditions in the experiment. Two models were considered to analyze drivers' mean speed separately for each transition zone, i.e., Model 1 for the first transition zone (from 120 to 100 km/h) and Model 2 for the second transition zone (from 100 to 80 km/h). Within-subject ANOVA tests were conducted for both models separately to analyze drivers' mean speed. Post-hoc analyses were conducted to understand the effect of the different conditions examined on the speed at specific locations.

For the lateral position, the data was extracted in 6 equal subsections of 50 m long between the seven analysis points. Unlike the point-based data extraction, this method was used to investigate the variations in drivers' lateral position in the predefined sub-sections. For each participant, the SDLP was calculated in each subsection for all of the four conditions. The SDLP was selected instead of the mean value for the lateral position since STISIM contains both positive and negative values for the lateral position. Averaging positive and negative values would hide the exact behavior at specific points, so we opted for SDLP. Similar to the speed analyses, two models were considered to analyze drivers' mean SDLP separately for each transition zone.

For outlier analysis, a total of 56 combinations were considered (i.e., 4 conditions x 2 transition zones x 7 points). Participants identified as an outlier (1.5 interquartile range from the group's mean) in more than 15% of combinations were removed (Ariën et al., 2013; Hussain et al., 2020c).

4. RESULTS

4.1. Analysis of speed

Table 2 presents the results obtained from the ANOVA tests for speed at a 95% confidence interval. Model 1 analyzed drivers' traveling speed for the first transition zone (120 to 100 km/h). Results indicated a significant main effect of the factors 'Condition' ($F_{(3,216)} = 4.1$, $p = .009$) and 'Point' ($F_{(2,127)} = 233.0$, $p < .001$). This means that drivers' traveling speed was significantly influenced due to the tested conditions and across the 7 points independent of any other factor. The interaction effect of 'Condition x Point' was also statistically significant ($F_{(5,392)} = 2.7$, $p = .021$), meaning that drivers' travel speed was significantly different among the tested conditions taken across the analysis points. Models 2 analyzed speed for the second transition zone (100 to 80 km/h). Results revealed significant main effects of the factors 'Condition' ($F_{(3,197)} = 3.9$, $p = .01$) and 'Point' ($F_{(2,144)} = 318.7$, $p < .001$). Unlike the results for Model 1, the interaction effect was not significant in this model. This implies that drivers' traveling speed was not significantly influenced across the analysis points due to the four tested conditions. However, this might be because of the similar speed reduction in the treatment conditions. Therefore, to investigate this in more detail, we further analyzed the pairwise mean differences between all conditions on different analysis points.

Table 2
ANOVA tests for analysis of speed (Greenhouse-Geisser corrected)

Models	Effect	F	Dfs	p
Model 1 (Transition zone 1: 120 to 100 km/h)	Condition	4.1	3, 216	.009
	Point	233.0	2, 127	<.001
	Condition x Point	2.7	5, 392	.021
Model 2 (Transition zone 2: 100 to 80 km/h)	Condition	3.9	3, 197	.01
	Point	318.7	2, 144	<.001
	Condition x Point	4.6	5, 351	.305

Significance level α = 0.05.

Table 3
Pairwise comparisons and ANOVA tests for speed differences at analysis points for Transition zone 2 (100 to 80 km/h)

Location (m)	Condition	Control	Size	Brightness	Combined
−200	Control	-	2.1	2.1	2.5
	Size		-	−0.1	0.3
	Brightness			-	0.3
	Combined				-
	ANOVA test	*F(3,308) = 1.0, ηp² = .010, p-value = .375*			
−150	Control	-	2.2	2.4	2.4
	Size		-	0.2	0.2
	Brightness			-	<.1
	Combined				-
	ANOVA test	*F(3,308) <1, ηp² = .010, p-value = .396*			
−100	Control	-	2.5	**3.8***	**3.9***
	Size		-	1.3	1.4
	Brightness			-	0.1
	Combined				-
	ANOVA test	*F(3,308) = 2.0, ηp² = .019, p-value = .111*			
−50	Control	-	2.7	**4.4****	**4.6****
	Size		-	1.6	1.8
	Brightness			-	0.2
	Combined				-
	ANOVA test	*F(3,308) = 2.7, ηp² = .026, p-value = **.046****			
0	Control	-	2.4	**4.5****	**4.5****
	Size		-	2.1	2.1
	Brightness			-	0.1
	Combined				-
	ANOVA test	*F(3,308) = 2.7, ηp² = .026, p-value = **.044****			
50	Control	-	1.8	**3.7****	**4.1****
	Size		-	2.0	2.3
	Brightness			-	0.4
	Combined				-
	ANOVA test	*F(3,308) = 2.2, ηp² = .021, p-value = .085*			
100	Control	-	1.2	**3.1***	**3.2****
	Size		-	1.9	2.0
	Brightness			-	0.1
	Combined				-
	ANOVA test	*F(3,308) = 1.5, ηp² = .014, p-value = .218*			

Significance is indicated with bold font: α = 0.01**, 0.05*

Table 3 presents the pairwise mean differences for traveling speed between all conditions at the analysis points at Transition zone 1. To understand if the differences between the conditions along different locations were statistically significantly different, a series of t-tests (two-tailed/paired) were conducted. Also, separate ANOVA tests were conducted at each level of the analysis point to investigate if the tested conditions' differences were significant for that specific point. The statistically significant differences are indicated in bold, while the number of asterisks indicates the significance level. The ANOVA tests results revealed that drivers' travel speed was not significantly influenced among the tested conditions until the start of the pavement markings (i.e., at -100 m point). The pairwise comparisons showed that compared to the "Control" condition, traveling speed was significantly reduced in the

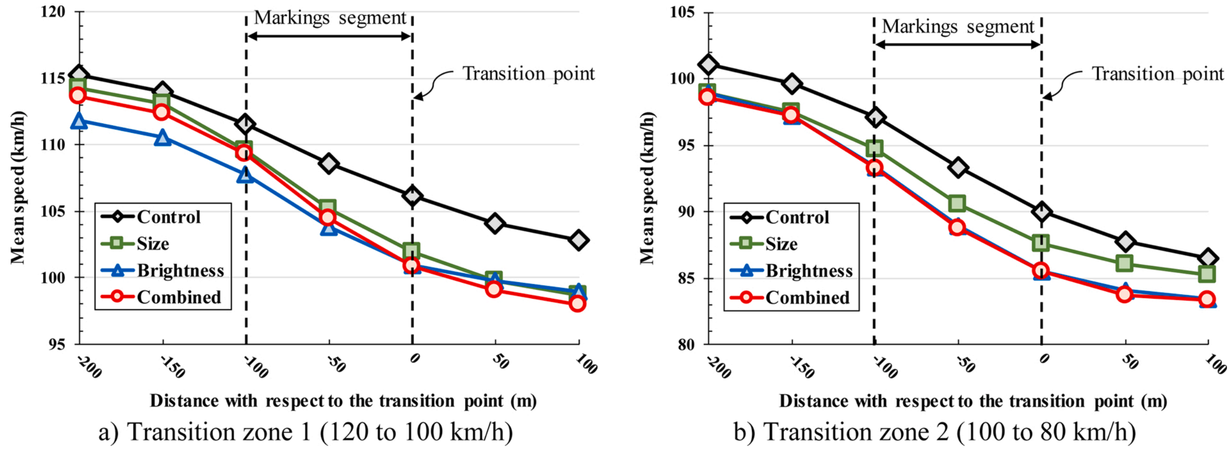


Fig. 3. Mean speed profiles for each condition at both transition zones

Table 4
Pairwise comparisons and ANOVA tests for speed differences at analysis points for Transition zone 1 (120 to 100 km/h)

Location (m)	Condition	Control	Size	Brightness	Combined
−200	Control	-	0.9	**3.4***	1.6
	Size		-	2.4	0.6
	Brightness			-	−1.8
	Combined				-
	ANOVA test	*F(3,308) = 1.4, ηp² = .013, p-value = .251*			
−150	Control	-	0.9	**3.4***	1.6
	Size		-	2.5	0.7
	Brightness			-	−1.8
	Combined				-
	ANOVA test	*F(3,308) = 1.4, ηp² = .013, p-value = .253*			
−100	Control	-	1.9	**3.8****	2.3
	Size		-	1.8	0.3
	Brightness			-	−1.5
	Combined				-
	ANOVA test	*F(3,308) = 1.4, ηp² = .014, p-value = .229*			
−50	Control	-	**3.4***	**4.8****	**4.1***
	Size		-	1.4	0.8
	Brightness			-	−0.6
	Combined				-
	ANOVA test	*F(3,308) = 2.7, ηp² = .025, p-value =* ***.047****			
0	Control	-	**4.2****	**5.2****	**5.3****
	Size		-	0.9	1.1
	Brightness			-	0.1
	Combined				-
	ANOVA test	*F(3,308) = 4.1, ηp² = .039, p-value =* ***.006*****			
50	Control	-	**4.3****	**4.4****	**5.1****
	Size		-	0.1	0.8
	Brightness			-	0.7
	Combined				-
	ANOVA test	*F(3,308) = 4.0, ηp² = .037, p-value =* ***.008*****			
100	Control	-	**4.1****	**3.9****	**4.8****
	Size		-	−0.3	0.7
	Brightness			-	0.9
	Combined				-
	ANOVA test	*F(3,308) = 3.7, ηp² = .035, p-value =* ***.012****			

Significance is indicated with bold font: α = 0.01**, 0.05*

conditions with pavement markings at different locations. The highest speed reductions were observed at the transition point, i.e., 5.3 km/h speed reduction in the "Combined" condition followed by 5.2 km/h speed reduction in the "Brightness" condition. At the same point, a 4.2 km/h speed reduction was observed in the "Size" condition. The reductions in speed at the transition point and afterward were significant at a 99% confidence level for all the treatment conditions. Results for mean speed are also visually illustrated in Fig. 3(a) by means of mean speed profiles.

Table 4 presents the pairwise mean differences in traveling speed between all conditions at the analysis points at Transition zone 2. Again, the highest speed reduction (i.e., 4.6 km/h) was observed in the "Combined" condition followed by the "Brightness" condition (i.e., 4.4 km/h) in the middle of the marking segment. At this location (-50 m), the difference in speed between the "Control" and "Size" conditions was not statistically significant. In addition, at the entrance point (0 m), the highest and equal speed reduction was observed for both the "Combined" and the "Brightness" conditions (4.5 km/h). The speed reduction values were significant at a 99% significance level in the "Combined" condition from the middle of the marking segment until the end of the analysis segment. However, the significance level was reduced in the "Brightness" condition, 100 m after the transition point. Different from the results from Transition zone 1, traveling speed was not significantly reduced for the condition with pavement markings based on size. In most of the cases, the values of the speed reduction observed at the second transition were lower than those observed at the second transition. The mean speed profiles are visualized for the analysis section of the second transition zone (see Fig. 3(b)). It is clear from the plot that compared to the pavement marking treatments implemented (especially the "Combined" and "Brightness" treatments), drivers' traveling speed was higher throughout the segment in the "Control" condition.

Fig. 4 presents the acceleration/deceleration (ACC/DEC) rates at each analysis point and for each condition to further explore the rate of change in drivers' speed values. It is clear from the plots that compared to the second transition zone, drivers decelerated with higher rates at the first transition zone. It is also visible from the plots that drivers' deceleration rates were higher in the treatment conditions than the "Control condition. The lowest ACC/DEC rates of -1.13 m/s2 and -0.70 m/s2 were observed in the "Combined" condition at the start of the marking segments, at the first and second transition zones, respectively. Compared to the "Control" condition, the ACC/DEC rates were lowered by -0.72 m/s2 and -0.22 m/s2 in the "Combined" condition at the start of the marking segments, in the first and second transition zones, respectively.

4.2. Analysis of demographic characteristics and speed

To investigate if the treatments had impacts on socio-demographic characteristics in terms of speed reduction, a between-subject ANOVA test was estimated for two-way interaction effects between the factor "Condition", and the demographic factors, i.e., Gender (male, female), Ethnicity (Arab, non-Arab), Age (18-30, 31-40, >40 years) and Experience (1-10, more than 10 years). The analysis was conducted, taking the analysis sections of both transition zones together. The results showed a significant interaction effect for "Condition x Gender" ($F_{(3,4340)} = 5.25$, $p < .001$), meaning that the treatments influenced male drivers' speed behavior significantly different than female drivers. Moreover, all the

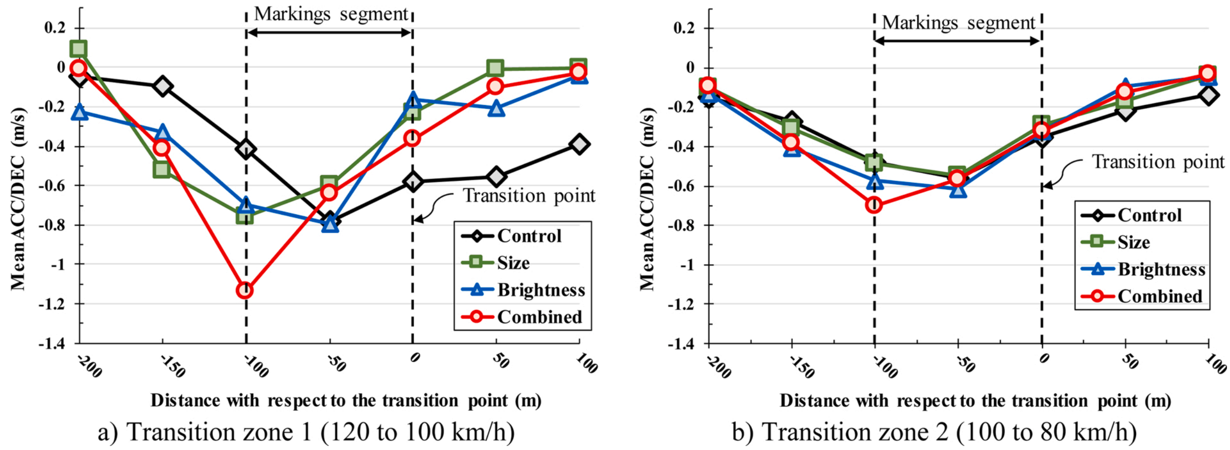


Fig. 4. Mean ACC/DEC profiles for each condition at both transition zones

Table 5
Mean speed differences between males and females, in each treatment condition compared to the control condition

Gender	Size*		Brightness*		Combined*	
	Mean speed reduction	P-value	Mean speed reduction	P-value	Mean speed reduction	P-value
Male Female	2.75 1.84	.378	2.89 5.87	.003	2.73 5.52	.013

* Mean speed reduction = Control condition – Treatment condition

Table 6
Analysis of standard deviation of lateral position SDLP: Within-subject ANOVA tests (Greenhouse-Geisser corrected).

Models	Effect	F	Dfs	p
Model 3 (Transition zone 1: 120 to 100 km/h)	Condition	3.1	3, 210	.033
	Subsection	1.3	3, 266	.258
	Condition x Subsection	<1	8, 634	.507
Model 4 (Transition zone 2: 100 to 80 km/h)	Condition	4.2	3, 207	.008
	Subsection	<1	4, 296	.546
	Condition x Subsection	1.2	8, 611	.292

Significance level α = 0.05.

other interaction effects were not significant, i.e., “Condition x Ethnicity” ($F_{(3,4340)}$<1, p = .19), “Condition x Age” ($F_{(6,4340)}$<1, p = .56) and “Condition x Experience” ($F_{(3,4340)}$<1, p = .58).

As the interaction effect of "Condition x Gender" was significant, a series of t-tests (two-tailed/independent samples) were conducted to investigate if the treatment conditions’ speed reductions were significantly different between males and females. Table 5 presents the speed reduction in each treatment condition compared to the control condition, for both males and females separately. The results showed that the mean speed reduction in the size condition was not significantly different between genders. However, the mean speed reductions were significantly higher for females compared to males in the “Brightness” ($t_{(412)}$= -2.9, p = .003) and “Combined” ($t_{(394)}$= -2.5, p = .013) conditions. This indicates that the pavement markings with brightness and combined concepts had higher impacts on females than males.

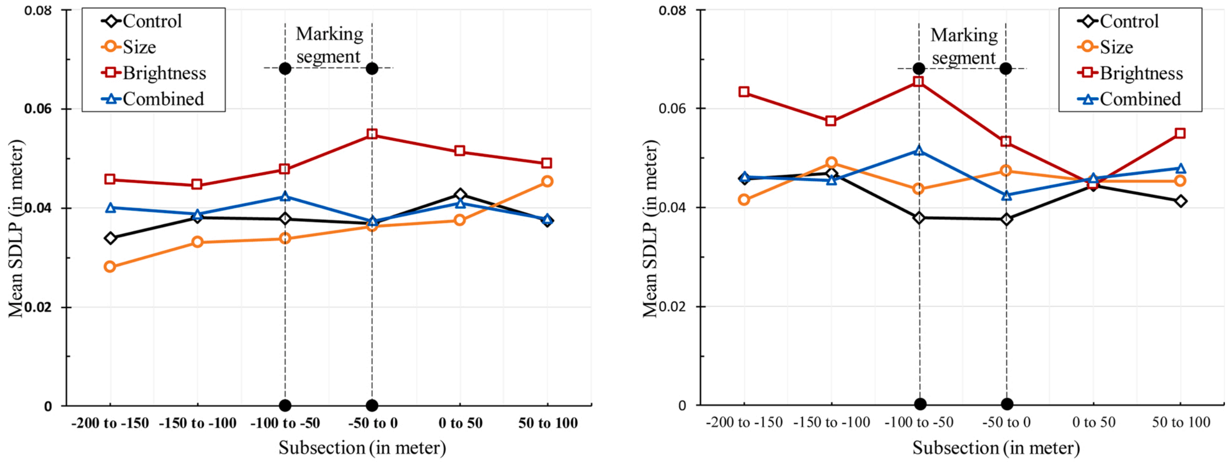
4.3. Analysis of SDLP

In this study, the lateral position was measured as the displacement from the center of the simulator mockup to the center of the driving lane irrespective of which lane the participants were driving on. Table 6 presents the ANOVA tests’ results regarding SDLP for Transition zone 1 (Model 3) and Transition zone 2 (Model 4). The ANOVA tests show a significant main effect for the factor Condition in both models [Transition zone 1: ($F_{(3,210)}$ = 3.1, p = .033); Transition zone 2: ($F_{(3,207)}$ = 4.2, p = .008)]. This means that independent of the factor ’Subsection’, the lateral position variation was significantly different between the conditions. The mean SDLP values along the overall analysis segment were 0.038 m, 0.036 m, 0.047 m, and 0.04 m for the "Control", "Size", "Brightness", and "Combined" conditions, respectively. Furthermore, in both the models, the main effect for the factor ’Subsection’ and the interaction effect for the factors’ Condition x Subsection’ were not significant, which means that the differences in SDLP were not statistically significant between the tested conditions over a total length of six subsections taken separately. The interaction effect results for Transition zone 1 and Transition zone 2 are illustrated in Fig. 5a) & b), respectively. It can be seen that the SDLP observed in the "Brightness" condition was marginally higher than the other conditions at both transition zones, with the highest value of approximately 0.065 m in the middle of the marking segment at the second transition.

5. DISCUSSION

This study investigates the effectiveness of different speed limit pavement markings to stimulate drivers to reduce their traveling speed while entering lower speed zones. Transition zones are usually equipped with speed limit posted signs only (van Schagen, 2003). Yet, roadside posted signs are situated in the peripheral field of view, so they are less frequently observed than information cues located in the central field of view (Briggs et al., 2018). Repetitive use of speed limit information might help drivers make correct speed choices (Charlton & Starkey, 2017). The optical characteristics of the pavement marking that were manipulated in this study were brightness and size. The relevance of focusing on these two optical features was derived from available literature on the phenomenon of depth perception through changes in size and brightness (Epstein & Landauer, 1969; Gogel, 1964; Higashiyama, 1977; Higashiyama & Adachi, 2006; Johns and Sumner, 1948; Landauer & Epstein, 1969; Ross & Plug, 1998; Sundet, 1978; Taylor and Sumner, 1945).

Results showed that pavement markings were effective in significantly reducing vehicle speed at the transition zones. Compared to the "Control" condition, the tested pavement marking treatments stimulated drivers to keep their traveling speed below the speed limit (100 km/h)



a) at Transition zone 1 (120 to 100 km/h) b) at Transition zone 2 (100 to 80 km/h)

Fig. 5. Standard deviation of lateral position (SDLP) for different subsections

after entering the first transition. On the other hand, the traveling speed was not reduced up to the speed limit (80 km/h) after entering the second transition in any of the tested conditions, with the lowest speed of 83.3 km/h observed for the "Combined" condition 100 m after the transition point. This might be because drivers' desired speed was higher than the speed limit prescribed for roads in an urban area after the second transition (Goldenbeld & van Schagen, 2007). Comparable results were observed in a real-world study on the same road (i.e., Doha Expressway), showing that in the case of a hidden speedometer, drivers drove faster than the requested speed of 80 km/h while slower than the requested speed of 100 km/h (Hussain et al., 2019b). In addition, speed was not reduced to the speed limit in the "Control" condition, not even after 800 m of the first transition (200 m before the second transition as shown in Fig. 4), highlighting the need for countermeasures to improve drivers' speed adaptation.

The largest speed reductions were observed in the "Combined" condition, i.e., mean speed reductions of 5.3 km/h (at entrance point in transition zone 1) and 4.5 km/h (at the entrance point of transition zone 2) lower compared to the "Control" condition. When looking at the observed effects for the different marking treatments individually, speed reduction was higher in the "Brightness" condition than the "Size" condition. This indicates that the proposed manipulation of brightness could generate better effects than the proposed manipulation of size.

Regarding the variation of lateral position (i.e., SDLP), results obtained with ANOVA-analysis show that this driving parameter differed statistically across the different conditions. The mean values for SDLP observed in previous studies range from 0.07 m to 0.41 m (Ariën et al., 2013; Auberlet et al., 2010; Auberlet et al., 2012; Bella, 2013; Cuenen et al., 2019; Daniels et al., 2010; Horberry et al., 2006; Hussain et al., 2018) while we found maximum value of approximately 0.065 m. According to Verster & Roth (2011), vehicle lateral control reduces as the SDLP value increases, e.g., values higher than 0.3 m could result in crossing into the adjacent traffic lane. However, our results with smaller SDLP values (less than 0.065 m) indicate that the proposed pavement markings did not negatively influence drivers' lateral control on the road.

6. LIMITATIONS AND FUTURE RESEARCH

It is essential to highlight that there are certain limitations associated with this study. It is not possible to verify whether the observed speed reductions were due to repeated exposure to the speed limit information provided or the generation of the envisaged perceptual effect (i.e., biased perception of distance). Future research could investigate if the manipulation of size and brightness in pavement markings produces the impression of increased speed. It would also be interesting for future research to test pavement markings with a different design, size/brightness ratio, and spacing between polygons. Furthermore, this study only focused on the immediate effects of the proposed treatments. It remains unclear to what extent these short-term effects would sustain over time. Finally, the participants were tested once for each condition during one driving session because of the length of the two test drives (i.e., 16 km each). Testing the conditions in multiple sessions may produce different results.

One of the practical limitations of the proposed pavement markings could be that they cover a large area over the 100 m road segment and may create a potential hazard on a wet surface, particularly for motorcyclists. However, paint having adequate skid resistance could be used to minimize the risk of skidding (Harlow, 2005; Venkata et al., 2010). Another limitation of the proposed pavement markings (especially pavement markings with the combined or brightness conditions) in the real-world could be the visibility issues under extreme weather (e.g., rain or snow) or night-time conditions. However, research studies indicate that using different materials in paint, such as retro-reflective, could significantly overcome these issues (Babić et al., 2020; Diamandouros & Gatscha, 2016). Another limitation of the proposed pavement markings in the real-world would be the implementation and maintenance costs, considering the gradual increase in size and brightness. However, using materials with longer service life, e.g., fluorescent thermoplastic materials with an average service life of two years, could overcome these costs (Federal Highway Administration, 2005).

7. CONCLUSION

This study evaluated the impact of optical features (i.e., brightness and size) of pavement markings on drivers' speed and standard deviation of lateral position at transition zones using a driving simulator. The study's primary findings were that the speed limit pavement markings based on the combined concepts and the grayscale luminance were effective in stimulating drivers to reduce their traveling speed at both transition zones significantly. Furthermore, the study results showed that markings with a gradual increase in brightness were more effective than that with a gradual increase in size in terms of speed reduction. Although variations in lateral position were significantly different among the tested conditions, the variations' values were negligible.

In conclusion, the visual patterns produced by brightness and size could improve safety at transition zones on expressways by stimulating drivers to adapt their speed. We recommend the proposed speed limit pavement markings with adequate skid resistance based on combined concepts as a low-cost speed calming measure to be utilized in rural-urban road transition zones.

CRediT authorship contribution statement

Qinaat Hussain: Conceptualization, Software, Methodology, Formal analysis, Investigation, Writing - original draft. **Wael K.M. Alhajyaseen:** Funding acquisition, Supervision, Project administration, Resources, Writing - review & editing. **Nora Reinolsmann:** Investigation, Formal analysis, Writing - review & editing. **Kris Brijs:** Conceptualization, Validation, Writing - review & editing. **Ali Pirdavani:** Methodology, Writing - review & editing. **Geert Wets:** Writing - review & editing. **Tom Brijs:** Methodology, Writing - review & editing.

Declaration of Competing Interest

We have no conflict of interest to declare.

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